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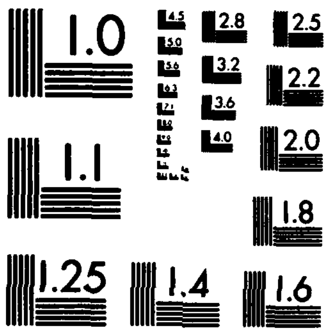

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ON MEASURING THE ACOUSTIC INTENSITY OF HYDROACOUSTIC SOURCES

G. C. Lauchle

Technical Memorandum
File No. TM 84-91
25 May 1984
Contract N00024-79-C-6043

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER TM 84-91	2. GOVT ACCESSION NO. AD-A142 484	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ON MEASURING THE ACOUSTIC INTENSITY OF HYDROACOUSTIC SOURCES		5. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) G. C. Lauchle		8. CONTRACT OR GRANT NUMBER(s) N00024-79-C-6043
9. PERFORMING ORGANIZATION NAME AND ADDRESS Applied Research Laboratory Post Office Box 30 State College, PA 16804		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command, Code NSEA 63R31 Department of the Navy Washington, DC 20362		12. REPORT DATE 25 May 1984
		13. NUMBER OF PAGES 20
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

acoustic intensity
hydroacoustics

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

With the recent interest in using the two-microphone technique to measure acoustic intensity, fundamental questions arise when considering this method for hydroacoustic studies. The acoustic intensity generated by a hydrodynamic source is related solely to those pressure components that propagate. The basic questions are then, what influence does the non-propagating hydrodynamic pressure fluctuations have on the intensity probe when used in the nearfield of the source and can their effect be removed

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Subject: On Measuring the Acoustic Intensity of Hydroacoustic Sources

Abstract: With the recent interest in using the two-microphone technique to measure acoustic intensity, fundamental questions arise when considering this method for hydroacoustic studies. The acoustic intensity generated by a hydrodynamic source is related solely to those pressure components that propagate. The basic questions are then, what influence does the non-propagating hydrodynamic pressure fluctuations have on the intensity probe when used in the nearfield of the source and can their effect be removed from a measured intensity spectrum? These two questions are addressed in this paper. An example indicates that the non-propagating pressure fields of a turbulent boundary layer flow can be accounted for approximately. The result is not generally applicable to three-dimensional fields, however.

Acknowledgment: This work was performed at the Applied Research Laboratory of The Pennsylvania State University under contract with the Naval Sea Systems Command, Code 63R31. Partial support for this work has also come from the IBM Corporation, Acoustics Laboratory, Poughkeepskie, NY.

I INTRODUCTION

The development and use of the two-sensor, cross-spectral density method for the measurement of acoustic intensity has proven to be a powerful tool in noise source diagnosis [1-5]. There has also been interest in using this technique in the presence or vicinity of low-speed (Mach number less than 0.1) turbulent flows [4,6-8]. The analysis of Lauchle [8] suggests that an intensity estimate for an acoustical source located outside of a turbulent boundary layer is basically unaffected by the presence of the boundary layer when the measurement is performed under this turbulent layer. This conclusion is founded upon the notion that the turbulent pressure fluctuations of the boundary layer are uncorrelated with the acoustic pressure generated by the source of interest.

A different, but related situation, deals with the measurement of the acoustical intensity generated by a hydrodynamic flow field. The word hydrodynamic is used to remind us that the flow field is of low enough mean velocity that it can be treated as incompressible. This also permits us to define intensity in the usual zero-flow manner [6]. It is further presumed that we would like to make this measurement in the nearfield of the hydrodynamic source. For example, one may need to map out the intensity vectors near the inlet opening of a centrifugal blower. The issues to be addressed then, are related to the interpretation of intensity spectra measured in these types of environments with the two-sensor method. It is the purpose of this paper to examine these issues and to consider, as an example, the measurement of the intensity spectrum generated by a turbulent boundary layer flow.

II. BASIC ANALYSIS

Consider the use of two pressure sensors of radius R in the measurement of acoustic intensity. This measurement requires the cross-spectral density function between the two sensors, where the intensity is then estimated from:

$$I_a(\omega) = -\frac{\mathrm{Im}\left[G_{12}(\omega)\right]}{\rho\omega\Delta x} \quad . \tag{1}$$

Here, Δx is the separation distance between the two sensors, ρ is the fluid mass density, G_{12} is the cross spectrum, and ω is the radian frequency. Equation (1) is valid at frequencies for which $k\Delta x \ll 1$ $\left(\Delta x < \lambda/6\right.$ is oftentimes used, where $\left.\lambda = 2\pi/k\right)$, where k is the sonic wavenumber, ω/c, with c being the velocity of sound.

If the two sensors are placed in a turbulent flow of mean velocity u_0 as generalized in Figure 1, the individual sensors will generate rms signals that contain both propagating and non-propagating components. If we let p_a denote the propagating pressure and p_T be that component associated with the non-propagating turbulent pressure fluctuations, it follows that

$$\hat{p}_1 = p_{a_1} + p_{T_1} \tag{2a}$$

and

$$\hat{p}_2 = p_{a_2} + p_{T_2} \quad . \tag{2b}$$

The cross spectrum between the measured rms pressures $\hat{p}_1$ and $\hat{p}_2$ therefore contains four terms, i.e.,

$$\hat{G}_{12} = G_{12} + G_{T_1T_2} + G_{a_1T_2} + G_{T_1a_2} \quad . \tag{3}$$

The notation used here is standard and follows Bendat and Piersol [9]; e.g.,

$$G_{12} = G_{p_{a_1} p_{a_2}} = \lim_{T\to\infty} \frac{2}{T} E\{P^*_{a_1}(\omega,T) P_{a_2}(\omega,T)\} \quad , \tag{4}$$

where P_{a_1} is the finite Fourier transform of p_{a_1} and the ensemble average is over many records. The asterick denotes complex conjugate.

Equation (3) is interpreted as follows: When the two pressure sensors are placed in a turbulent flow, the measured cross spectral density function will have four contributions. The first term, G_{12}, describes the contribution due to the propagating pressure field generated by the turbulence. The second term, $G_{T_1T_2}$, describes a cross spectrum associated with the non-propagating turbulent pressure field as measured at a sensor separation Δx. The last two terms, $G_{T_1a_2}$ and $G_{a_1T_2}$, describe the correlation of the non-propagating pressure at one sensor location with the propagating pressure sensed at the other location.

The objective set forth in this paper is to assess the usefulness of Equation (1) in measuring the acoustic intensity of a hypothetical hydro-acoustic source. From Equation (3) we see that the desired cross spectrum to be used in Equation (1) is of the form:

$$G_{12} = \hat{G}_{12} - G_{T_1T_2} - G_{a_1T_2} - G_{T_1a_2} \quad . \tag{5}$$

Clearly, $\hat{G}_{12}$ is measurable directly, but how do we estimate those cross spectra that need to be subtracted from $\hat{G}_{12}$? The answer to this question cannot be given in general because the space-time correlations among turbulent pressure fluctuation components depend strongly on the particular flow field being

studied. It is noted that when the acoustic source of interest is independent of the turbulent motions, the last two terms of Equation (5) are zero. This situation was studied by Lauchle [8] for boundary layer turbulence and by Oswald and Donavan [7] for free-stream turbulence. A detailed examination of Equation (5) for boundary layer turbulence would represent an extension of the previous analysis [8] and is given here.

III. AN EXAMPLE -- TURBULENT BOUNDARY LAYER

Let us consider the use of Equation (5) in Equation (1) when the sensors of Figure 1 are flush-mounted in a planar surface under a low-speed turbulent boundary layer (TBL). We assume that the TBL wall pressure fluctuations at the measurement locations are stationary, homogeneous, and of zero mean. The pressure autospectral density function measured by one of the sensors is given by [10]:

$$\hat{G}_{11}(\omega) \simeq \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \Phi(k_1,k_3,\omega)\left|H(k_1R,k_3R)\right|^2 dk_1 dk_3 \quad . \tag{6}$$

The wavenumbers k_1 and k_3 are those in the streamwise (x_1) and spanwise (x_3) directions, respectively. The wavenumber/frequency spectrum for the TBL wall pressure fluctuations, $\Phi(k_1,k_3,\omega)$ can be estimated using the analysis of Chase [11]. The wavenumber response function for circular sensors is given by [12]:

$$H(k_1R,k_3R) \simeq H(\underline{k}R) = \frac{2J_1(\underline{k}R)}{\underline{k}R} \quad , \tag{7}$$

where $\underline{k} = k_1^2 + k_3^2$, and J_1 is the Bessel function of order one. Corcos [13] gives general methods for calculating transducer spatial response functions

for arbitrarily-shaped sensors. He also shows that the cross spectrum $G_{T_1T_2}$ is sensitive to transducer spatial averaging effects as in Equation (6).

The wavenumber/frequency spectrum modeled by Chase [11] is characterized by a large energy region centered at the convective wavenumber, $k_c = \omega/u_c$, where u_c is the convection velocity given approximately by 0.7 u_0. This energy is non-propagating for low Mach number flows and represents the p_T-component of the present analysis. The p_a-component occurs at very low wavenumbers $k < k_c M_c$, where M_c is the convective Mach number, u_c/c. Inspection of Equation (6) together with Equation (7) shows that the p_T-component would dominate $\hat{G}_{11}$ for measurements using very small pressure sensors [13]. Haddle and Skudrzyk [14] used this same reasoning to show that p_a would dominate a measurement performed with very large transducers. They further showed that a fish-shaped sensor (major length in direction of flow) was less sensitive to the convective wavenumber pressure fluctuations than was a circular sensor of the same area.

The above discussion serves to indicate that the output of a flush-mounted pressure sensor under a TBL depends strongly on its shape and size. One could obtain a crude estimate of $G_{12} \sim \hat{G}_{12}$ by simply using large, fish-shaped sensors. This estimate would also require that $\Delta x > \Lambda$, where $\Lambda \simeq 11\pi/4k_c$ is the streamwise correlation length of the TBL pressure fluctuations [8]. If $\Delta x < \Lambda$, $G_{T_1T_2}$ would be non-negligible.

An estimate of G_{12} could possibly be improved by measuring, simultaneously, p_{T_1} and p_{T_2} and subtracting them from $\hat{p}_1$ and $\hat{p}_2$, respectively as in Equation (2). A potential method for doing this is sketched in Figure 2. The

fish-shaped sensors are fabricated from piezoceramic material and bored at the center to receive a "pin-hole" type microphone [15] or subminiature crystal. The center sensor would need to be isolated from the larger surrounding sensor by damping material. An analog differencing circuit would be used to form the differences:

$$p_{a_1} \approx \hat{p}_1 - p_{T_1} \tag{8a}$$

and

$$p_{a_2} \approx \hat{p}_2 - p_{T_2} \quad . \tag{8b}$$

The cross spectrum, G_{12}, would then be calculated directly from these two difference signals and used in Equation (1) to give a reasonable estimate of the intensity generated by the TBL in the streamwise direction. The concept is not restricted to the flow direction as long as the major length of the fish-shaped sensors align with the flow. Thus, the in-plane intensity vector could be obtained for various directions by re-positioning one element relative to the other, e.g., side-by-side positioning would yield I_a in the x_3-direction.

IV. CONCLUDING REMARKS

The illustrative example described above is perhaps the "simplest" hydroacoustic source in which a near-field intensity measurement can be interpreted. The fact that the TBL wall pressure field is two-dimensional and reasonably-well understood helps simplify the issues. The interpretation of $\hat{G}_{12}$ as measured by a pair of pressure sensors located in a general three-dimensional flow field is not nearly as well understood as the TBL case. Turbulent pressures generated in such fields are still highly dependent on wavenumber and frequency, but generalized modeling has yet to be accomplished. We would expect that the response of a three-dimensional pressure sensor to a three-dimensional turbulence field depends on sensor shape and size. It is not clear, however, how such sensors, particularly if they need to be large, can be placed in such fields without altering the hydrodynamic flow itself. It is therefore concluded that near-field measurments of the acoustic intensity generated by hydroacoustic sources of sound cannot be interpreted in general. Certain specific cases, such as the turbulent boundary layer, can however be explained.

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LIST OF FIGURES

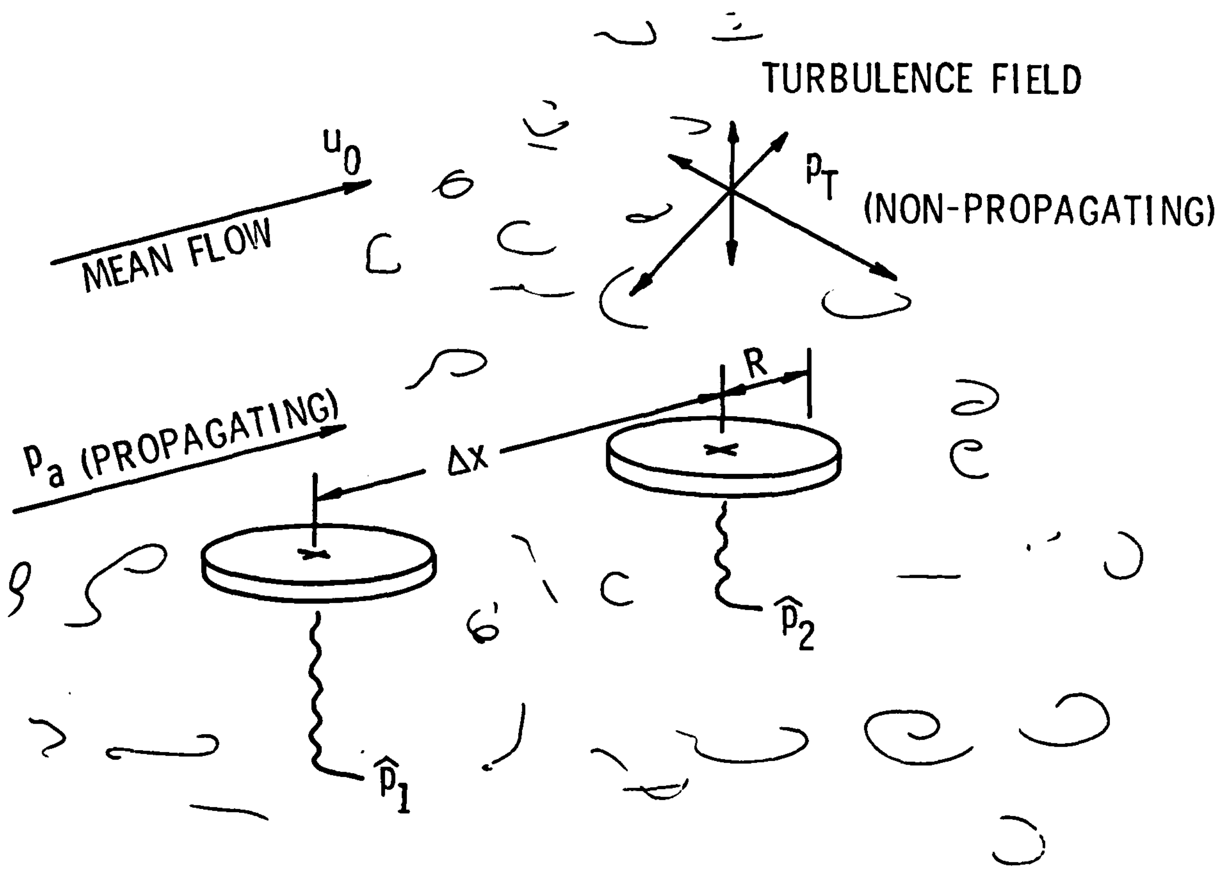

Figure 1. Hypothetical arrangement for the measurement of acoustic intensity in a turbulent flow.

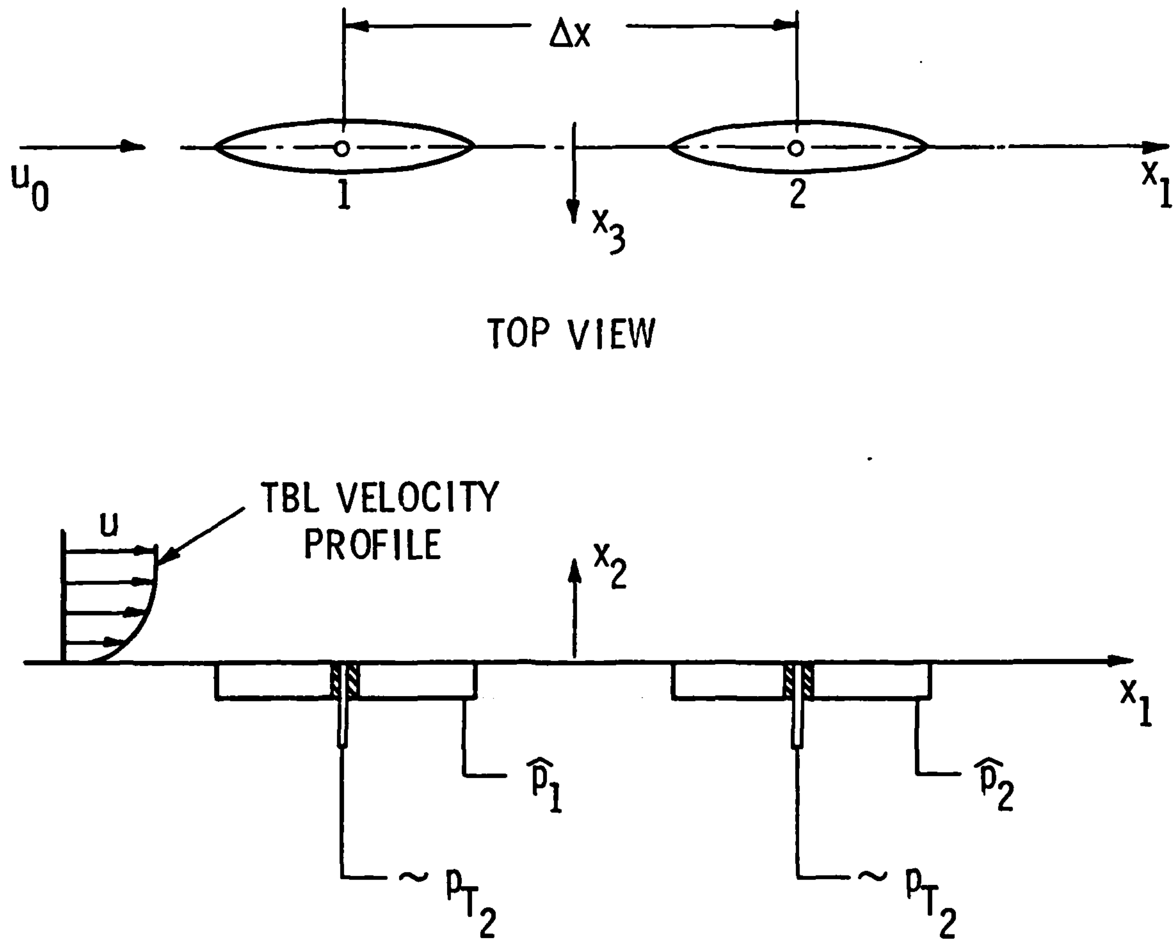

Figure 2. Suggested method for measuring the acoustic intensity of a TBL flow using sensors of special design that are placed under the TBL of interest.

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